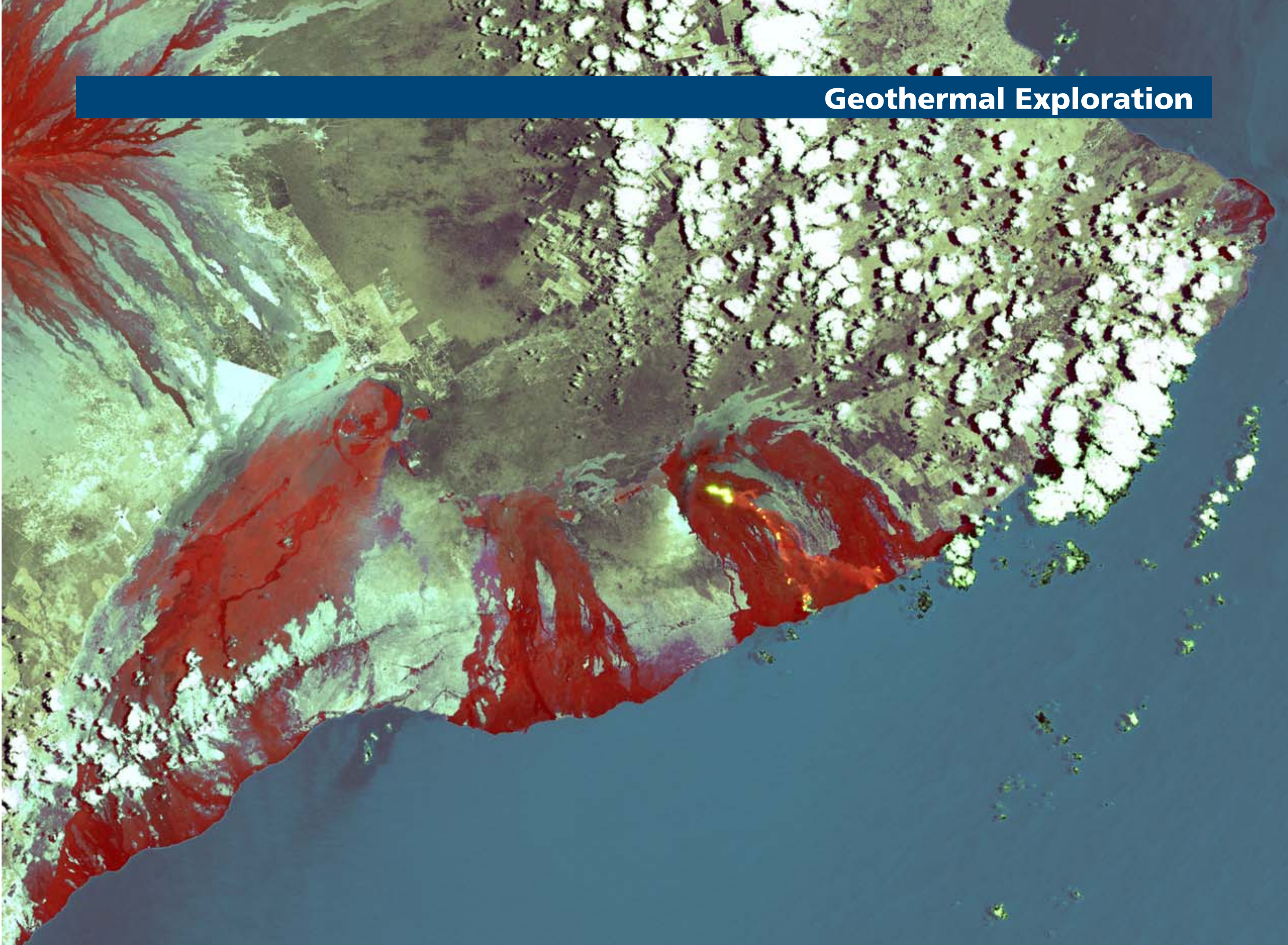

Good News or Bad?

New Study of Temperature Inversions in NSF Deep Geothermal Well at Kilauea Volcano

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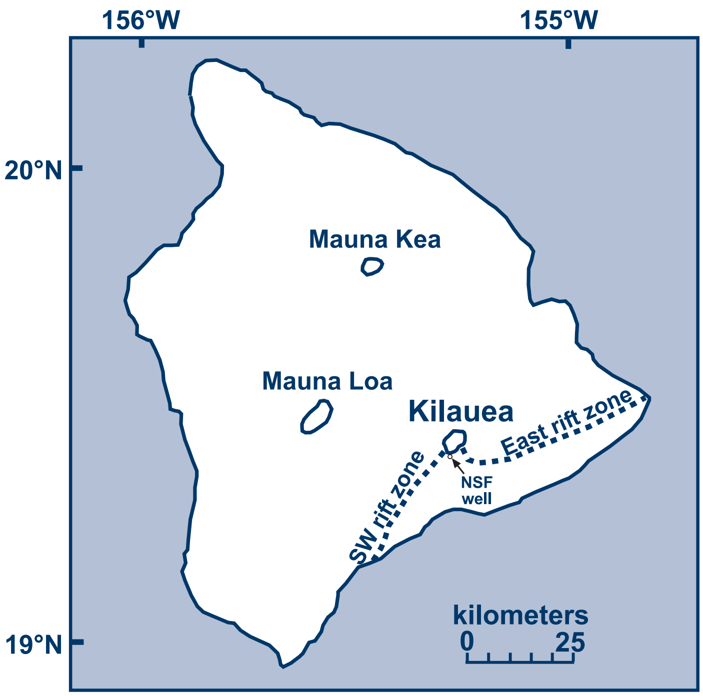
In some deep wells drilled in geothermal areas, temperature profiles show relatively cool isothermal zones overlying zones of steep positive and negative gradients. Where temperature gradient inversions are observed, the high-temperature sections are commonly assumed to represent ongoing lateral flow of hot fluid through thin aquifers embedded between low-permeability zones. For example, in many drill holes in the Great Basin, temperature inversions occur when hydrothermal fluids come up along a range-bounding fault and spread out in permeable sediments overlain by a conductive cap.

Inverse modeling of such temperature profiles can provide estimates of groundwater flow rates, heat fluxes, and the time that has elapsed between the onset of hydrothermal flow and the temperature measurement (Bodvarsson et al., 1982; Ziagos and Blackwell, 1986). In these models, quantitative solutions employing analytical or semi-analytical approaches invoke constant, homogeneous, and isotropic permeabilities, uniform initial fluid temperature, a fixed temperature or heat flux at the bottom of the simulation domain, and a constant lateral fluid flux.

Eastern tip of the Island of Hawaii, with Kilauea Volcano, its southerly lava flow and east-west rift zones, at bottom left-center. False color image courtesy of NASA Landsat Project Science Office / USGS EROS Data Center.



Map of the Island of Hawaii showing Kilauea Volcano and its two rift zones and the location of the NSF ("Keller") well.

In some cases, these simplifications are likely inappropriate. For example, in some deep wells relatively thick (>100 m) high-temperature sections are found. Further, temperature data obtained from fluid inclusions in secondary minerals often indicate that past fluid temperatures in the rock were higher (Bargar and Fournier, 1988; Bargar et al., 1995), whereas standard interpretations imply temperatures increasing towards a maximum at steady state. Laboratory experiments and thermodynamic, kinetic and thermoelastic considerations imply that in many cases hydrothermal fluid flow under a horizontal temperature gradient results in rapid mineral precipitation, rock contraction, and decreasing permeability with time (Moore et al., 1994; Martin and Lowell, 1997).

The National Science Foundation (NSF) Keller well on the summit of Kilauea Volcano on the Island of Hawaii was drilled in 1973 to a depth of 1,262 m from an elevation of 1,103 m. The well's temperature profile shows a nearly isothermal segment between land surface and the water table at approximately the mean annual air temperature; a sharp increase below the water table; and a high-temperature zone (maximum 92°C) to a depth of 720 m. The temperature then decreases to approximately 60°C between 900 and 1,000 m, then increases again to 137°C at the bottom of the hole.

Previous simulations of the temperature profile from the well concluded that it represents a free-convection cell within a closed domain (Keller et al., 1979). In this article, we provide an alternative interpretation of the complex temperature profile in the NSF well, which invokes a brief advective heating event followed by slow conductive cooling. This "transient lateral-flow" model also differs from earlier continuous lateral-flow models (Bodvarsson et al., 1982; Ziagos and Blackwell, 1986), and may be more suitable for this dynamic environment.

Our model allows for heterogeneous permeability, finite thickness of a thermal aquifer, evolving permeability, and a variety of boundary conditions. Because of these additional complexities, we use multi-phase numerical simulations rather than semi-analytical approaches to quantify the time scales associated with our transient lateral-flow model.

The Transient-Flow Model

We propose that episodic breaching of the deep hydrothermal system of Kilauea Volcano and opening of new vertical flow paths leads to the ascent of superheated fluid plumes along faults in the vicinity of Halemaumau pit crater, located in the southwest part of the caldera. Because of the large horizontal permeability of unaltered Hawaiian basalt flows, part of the ascending fluid plume is channeled laterally at shallow depths where rocks are as yet unaltered and are relatively permeable. This lateral flow causes thermoelastic expansion, precipitation of secondary minerals, and alteration of the host basalt, decreasing permeability and causing a relatively rapid transition from advection-dominated to conduction-dominated heat transport. We propose that such a lateral-flow event, and resultant permeability decrease, occurred between 490 m and 720 m depth, an interval now characterized by elevated temperatures in the NSF well. The postulated post lateral-flow cooling trend is consistent with alteration mineralogy from the NSF well core, which indicates higher temperatures (<140°C) and presumably higher flow rates/permeabilities in the past (Hurwitz et al., 2003). Such episodic hydrothermal activity would be consistent with observations from mid-ocean ridge hydrothermal systems, where temperature transients have been observed over time scales of weeks.

Geochemical data from the NSF well suggests a lateral-flow component, with recharge on the northern or eastern margins of the caldera and input of magmatic gases below Halemaumau pit crater (Hurwitz et al., 2003). These data strongly suggest an open flow system between the northern or east margins of the caldera and the NSF well, which is inconsistent with the convection cell model. Further, the free-convection model cannot readily account for the apparent cooling of the fluid from 300°C at Halemaumau to 92°C at the well.

Numerical simulations using the finite difference code HYDROTHERM (Hayba and Ingebritsen, 1994) for simulation of transient multi-phase flow of pure water and heat were carried out to examine the feasibility of this model and quantify the time scales involved. The code solves numerical approximations to mass and energy balance equations that are posed in terms of pressure and enthalpy under a wide range of temperature and pressure conditions. The numerical procedures, boundary conditions and details of controlling parameters are given in Hurwitz et al. (2002).

The two-dimensional cross-section (8 km long by 1.3 km deep) used to simulate the thermal regime below Kilauea summit consists of three units with distinct hydraulic properties: 1) a basal unit with permeability in the range of $1x10^{-18}$-$1x10^{-15}$ m^2 that represents the deep, linear part of the temperature profile; 2) an "aquifer unit" that represents the high temperature zone between 490 to 720 m with permeability and porosity (0.1 to 0.01) decreasing gradually during a single simulation from $3x10^{-11}$ m^2, representing unaltered Hawaiian basalt, to $1x10^{-15}$ m^2, representing altered basalt; and 3) a thin (10 m), upper unit with a constant horizontal and vertical permeability of $9x10^{-10}$ m^2 and $9x10^{-11}$ m^2, respectively.

This unit is dominated by vigorous cold groundwater recharge, which dissipates heat conducted from the high-temperature aquifer unit. The top of this unit is at the water table. Permeability in unit 2 was decreased at rates ranging from 1 log unit every 70 years to 1 log unit every 3,000 years until the lower permeability threshold was attained, and then held constant. A hydrothermal flux (300°C) was injected into unit 2, and was either held constant throughout the simulation (0.01 kg/sec/m^2), or decreased from 0.01 kg/sec/m^2 to a minimum of 0.001 kg/sec/m^2 over 5 to 50 years.

Aerial view of Kilauea from southwest rift zone looking northeast across the caldera. Halemaumau pit crater (right of center) is about 1 km in diameter and 85 m deep.

Two initial temperature conditions were considered. The first consists of an upper segment at 25°C, representing the "rain curtain effect" caused by groundwater recharge at mean annual temperature, and a lower segment with a linear temperature gradient of 560°C/km, linked by a smooth transition zone (t=0). The second set of initial temperature conditions consists of a 40°C/km thermal gradient from the upper boundary to the bottom of the aquifer unit and a 380°C/km gradient to the bottom of the domain.

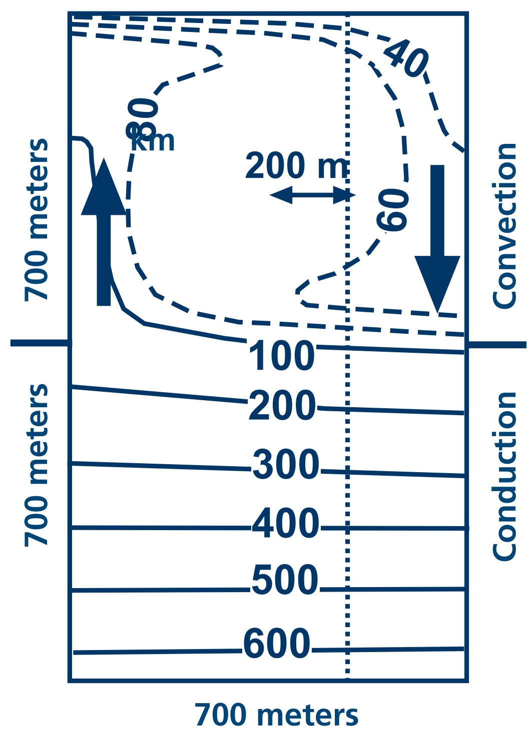
Results of Numerical Simulations

Numerical simulations were carried out for a range of parameters, and various combinations of parameters enabled successful matching of measured temperature profiles. The optimal match to the measured curve was determined by summing the difference between measured and calculated temperatures at each cell along the entire profile until a minimum value was obtained.

Simulation results were sensitive to the initial temperature distribution. A steeper initial temperature gradient (560°C/km) than that measured in the deep part of the NSF well (380°C/km) was required for optimal matching. This elevated temperature gradient implies a magmatic temperature of 1,200°C at a depth of 3.1 km, rather than 4.0 km as implied by the measured temperature gradient at the bottom of the well.

It takes 90 to 180 years to attain a maximum temperature of 120°-170°C in unit 2, after which temperatures cool gradually. It takes 750 to 1,000 simulation years to match the calculated and measured curves using the cooler initial condition. The match time is controlled primarily by conductive heating of the deep part of the profile throughout the low-permeability unit 1.

Continuous lateral-flow models such as those of Bodvarsson et al. (1982) and Ziagos and Blackwell (1986) imply widespread advective heating after 800 years. In our alternative transient lateral-flow model, the high temperature plume is limited to a narrow zone near Halemaumau after 800 simulation years (see figure showing contrasting thermal fields in cross-section).



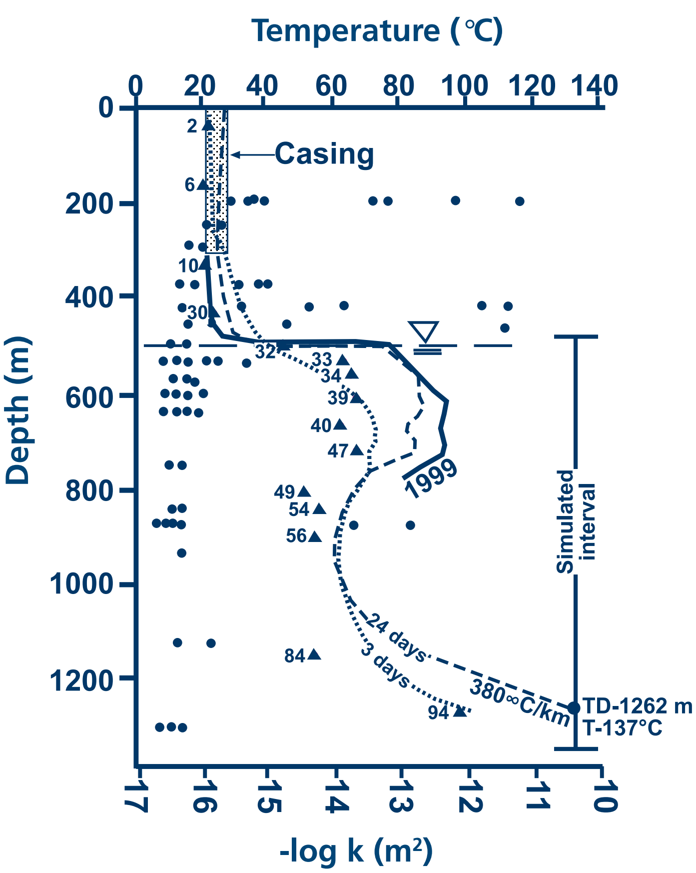
Calculated temperature distribution for the steady state convection model [Keller et al., 1979]. The best match to the measured temperature profile in the NSF well is 200 m from the center of the simulation domain, represented by the dashed vertical line. The arrows represent flow directions in this model.

Implications for Geothermal Exploration

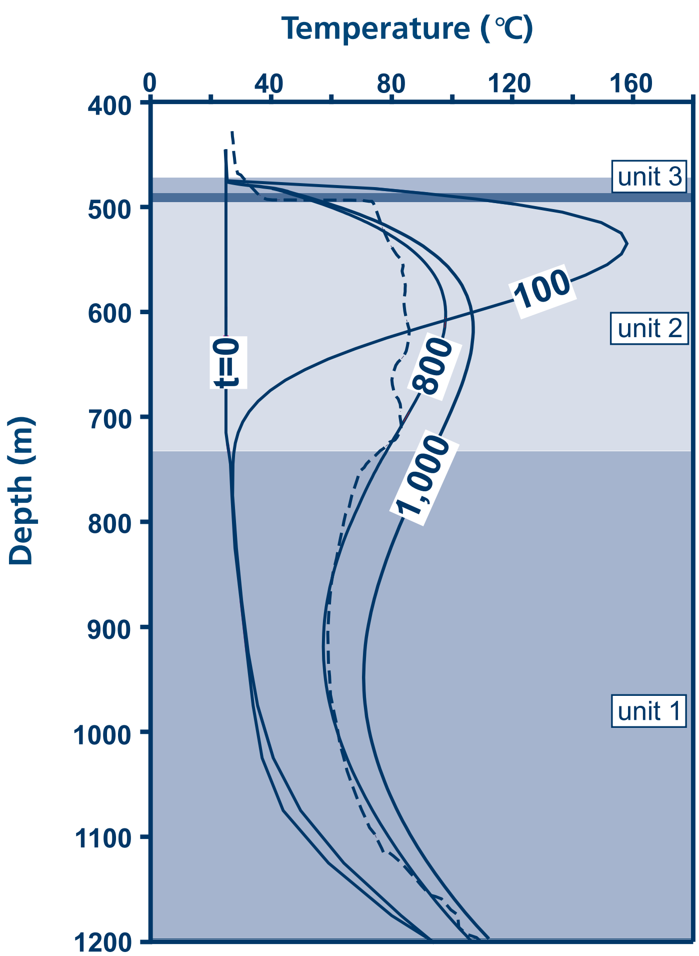
Implications of the transient lateral-flow model differ significantly from those of the steady-state free-convection model (Keller et al., 1979) and continuous lateral-flow models (Bodvarsson et al., 1982; Ziagos and Blackwell, 1986). In both of these latter models, temperature distribution is dominated by continuous advective transport. In our model, however, heat transport was initially dominated by advective transport, but as flow in the aquifer unit decreased with decreasing permeability, heat transport became dominated by conduction. If our model were correct, then drilling into unit 2 would result in very low yields. If either the steady convection or continuous lateral-flow models were correct, then drilling into the aquifer might result in a high yield of thermal water.

Although closed-domain free-convection models can match the measured temperature profile, they are neither consistent with isotopic data from the NSF well (which indicates recharge on the northern or eastern margins of the caldera), nor with geochemical data indicating input of magmatic gases below Halemaumau pit crater (Hurwitz et al., 2003). Further, the free-convection model cannot readily account for the apparent cooling of the fluid from 300℃ at Halemaumau to 92℃ at the well.

As noted by Ziagos and Blackwell (1986), it is difficult to apply their continuous lateral-flow model to the temperature profile in the NSF well. The “aquifer”unit is more than 200 m thick, and there are indications that the current permeability of that unit may be low. The permeability in cores recovered from the NSF well is generally less than 10^{-16} m^2 below the water



Temperature and permeability data from the NSF well on Kilauea summit. Numbered triangles represent bottom hole temperatures during drilling; the numbers indicate the number of days since drilling commenced (Keller et al., 1979). The dotted and dashed curves represent temperature profiles measured 3 and 24 days, respectively, after drilling was completed. The solid curve is the temperature profile measured in 1999. Dots represent core permeability (Keller et al., 1979). Also shown are the cased interval of the hole, the water-table elevation (dashed line at at depth of 488 m) and the depth interval simulated.



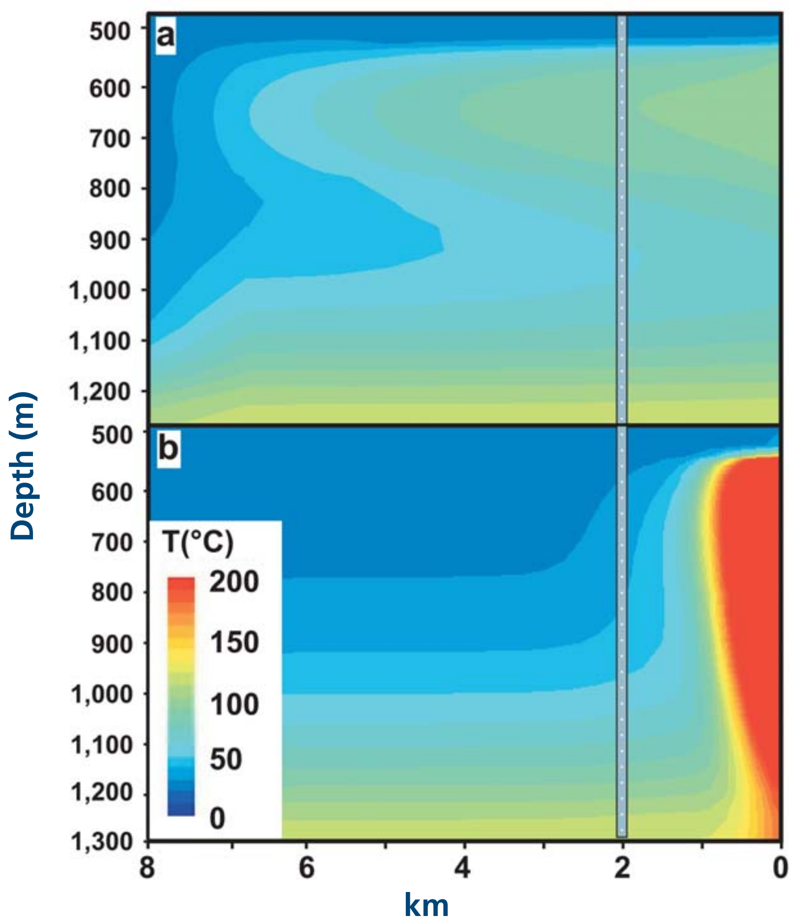
Calculated temperature profiles. Unit 1 - 1x10-15m2, in unit 2 initial horizontal and vertical permeabilities of 3x10-11m2 and 3x10-12m2 decreased by 1 log unit every 70 years until permeabilities of 1x10-15m2 (horizontal) and 1x10-16m2 (vertical) were attained. A flux of 0.01 kg/sec/m2 at 300℃ into unit 2 was specified for the first 30 years. Curves represent initial conditions (t=0) and temperature profiles after 100, 800 and 1,000 simulation years. The dashed curve is the measured temperature profile from 1973.

table. Though measurements of crystalline rock typically indicate that permeability is scale-dependent (Brace, 1984), thermoelastic stresses, mineral precipitation, and rock alteration tend to minimize this scale-dependence due to preferential sealing of cracks (Moore et al., 1994; Martin and Lowell, 1997).

Thus, in heavily altered rocks, core measurements and regional scale permeability may be similar. Observations during drilling do suggest a relatively high-permeability zone roughly coincident with the water table and above the high-temperature zone. At two points during drilling, the mud level in the well dropped to the water table and then stabilized, suggesting outflow from the hole at that depth.

Though we believe that our transient lateral-flow model is a plausible alternative, it does not provide a perfect match to the observed temperature profile in the NSF well. Conductive dissipation of heat following a finite lateral-flow event leads to a smooth, bell-shaped thermal anomaly; in particular, the upper boundary of the simulated high-temperature zone is less abrupt than the measured profile. If the measured profile accurately represents formation conditions, the actual situation must be more complex than our simple model.

Brief episodic events such as those invoked in our model imply that temperature inversions may be observed in some volcanic systems a few thousands of years after flow has essentially ceased, and cannot always be attributed to active circulation. Independent knowledge of permeability, fluid chemistry and volcano history may be essential in order to arrive at unique interpretations. Temperature inversions are usually "bad news" from a thermal perspective. Where our alternative model applies, they may be "bad news" from the standpoint of productivity as well.



Temperature distribution after 800 simulation years for (a) model with continuous flow of thermal water (92°C) through the aquifier unit and constant permeability and (b) model with transient lateral-flow.

Acknowledgments

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